SYSTEM AND METHOD FOR CORRECTING 3D EFFECTS IN AN ALTERNATING PHASE-SHIFTING MASK

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RELATED APPLICATIONS

[0001] This application is a divisional of U.S. Patent Application 09/974,507, entitled "System And Method For Correcting 3D Effects In An Alternating Phase-Shifting Mask" filed October 9, 2001.

BACKGROUND OF THE INVENTION

Field of the Invention

[0002] This invention relates to the field of alternating phase-shifting masks, and in particular to a method of correcting three-dimensional (3D) effects in alternating phase-shifting masks using two-dimensional (2D) analysis.

Description of Related Art

[0003] To fabricate an integrated circuit (IC), a physical representation of the features of the IC, e.g. a layout, is transferred onto a plurality of masks. The features make up the individual components of the circuit, such as gate electrodes, field oxidation regions, diffusion regions, metal interconnections, and so on. A mask is generally created for each layer of the IC. To create a mask, the data representing the layout for a corresponding IC layer can be input into a device, such as an electron beam machine, which writes IC features onto the mask. Once a mask has been created, the pattern on the mask can be transferred onto the wafer surface using a lithographic process.

[0004] Lithography is a process whose input is a mask and whose output includes the printed patterns on a wafer. As printed patterns on the IC become more complex, a need arises to decrease the feature size. However, as feature sizes shrink, the resolution limits of current optical-based lithographic systems are approached. Specifically, a lithographic mask includes clear regions and opaque regions, wherein the pattern of these two regions defines the features of a particular semiconductor layer. Under exposure conditions, diffraction effects at the transition of the transparent regions to the opaque regions can render these edges indistinct, thereby adversely affecting the resolution of the lithographic process.

[0005] Various techniques have been proposed to improve this resolution. One such technique, phase-shifting, uses phase destructive interference of the waves of incident light. Specifically, phase-shifting shifts the phase of a first region of incident light waves approximately 180 degrees relative to a second, adjacent region of incident light waves. In this manner, the projected images from these two regions destructively interfere where their edges overlap, thereby improving feature delineation and allowing greater feature density on the IC. A mask that uses such techniques is called a phase-shifting mask (PSM).

[0006] In one type of PSM, called an alternating (aperture) PSM, apertures between closely spaced features are processed so that light passing through any aperture is 180 degrees out of phase from the light passing through an adjacent aperture. Figures 1A and 1B illustrate one embodiment of an alternating PSM 100 including closely spaced opaque (e.g. chrome or some other absorbing material) features 101, 102, 103, and 104 formed on a transparent, e.g. quartz, substrate 105. Thus, apertures 106, 107, and 108 are formed between features 101-104.

[0007] To provide the phase-shifting in this embodiment, the areas of substrate 105 under alternating apertures can be etched, thereby causing the desired 180 degree phase shift. For example, substrate 105 can be etched in the area defined by aperture 107 to a predetermined depth. In this manner, the phase shift of light passing through aperture 107 relative to light passing through apertures 106 and 108 is approximately 180 degrees.

[0008] Unfortunately, the use of a PSM can introduce an intensity imbalance problem. Figure 1C illustrates a graph 130 that plots intensity (0 to 1.0) versus position on alternating PSM 100. In graph 130, waveforms 131 that are shown nearing 1.0 intensity correspond to apertures 106 and 108, whereas waveform 132 that is shown at approximately 0.84 intensity corresponds to aperture 107. The intensity imbalance between the 180 degree phase-shifting region (i.e. aperture 107) and the 0 degree phase-shifting regions (i.e. apertures 106 and 108) is caused by the trench cut into substrate 105, thereby causing diffraction in the corners of aperture 107 and degrading the intensity of the corresponding waveform. This industry-recognized diffraction effect is called a three-dimensional (3D) effect.

[0009] Intensity imbalance can adversely affect printing features and overlay on the wafer. Typically, a feature on a binary mask has a pair of corresponding phase-shifting regions on a PSM. For example, referring to Figure 1D, a feature 140 can have a corresponding 0 degree phase-shifting region 141 placed relative to one side of feature 140 and a corresponding 180 degree phase-shifting region 142 placed relative to the other side of feature 140. Of interest, if phase-shifting regions 141 and 142 are the same size, the electric field associated with region 141 is stronger than the electric field associated with region 142, thereby resulting in the maximum interference of these fields to occur to the right of centerline 143 on feature

140. Thus, under these conditions, feature 140 will actually print on the wafer to the right of the desired location as shown by feature 150 and its associated centerline 153.

[0010] Moreover, any defocus in the system can exacerbate the 3D effect and cause significant deviation from desired feature placement on the wafer. Because any wafer production line requires at least some acceptable range of defocus, e.g. typically within 0.4 microns, feature placement is frequently adversely affected when using alternating PSM. Therefore, those in the industry have proposed various methods to address the intensity imbalance problem.

[0011] In one proposed method shown in Figure 1E, an additional etching step can be performed on substrate 105, thereby providing an under-cut etch 160 of features 101-104. Under-cut etch 160 increases the intensity by attempting to localize the diffraction effects under features 101-104. Unfortunately, under-cut etch 160 can also create mechanical instability of features 101-104 on the mask. In fact, the more the diffraction effects are localized, the greater the probability of mechanical instability during subsequent processing steps, such as mask cleaning. Thus, under-cut etch 160 provides an incomplete solution with the potential of causing complete mask failure.

SUMMARY OF THE INVENTION

[0012] In accordance with one feature of the present invention, an accurate, cost-effective system and method for correcting three-dimensional effects on an alternating phase-shifting mask (PSM) is provided. To facilitate this correction, a method of building a library used for creating the alternating PSM can be provided. The method can include determining a first group of 180 degree phase-shifting regions, wherein the first

group of 180 degree phase-shifting regions have a common first size. Three-dimensional (3D) simulation can be performed based on this first size. Of importance, a transmission and a phase can be altered in a 2D simulation based on this first size until a shape dependent transmission and a shape dependent phase allow the 2D simulation to substantially match the 3D simulation. Finally, a modified first size can be chosen using the shape dependent transmission and the shape dependent phase such that a 2D simulation based on the modified first size substantially matches the 3D simulation based on the first size. The library can associate the first size with the modified first size, the shape dependent transmission, and the shape dependent phase.

[0013] This method can be repeated for a plurality of groups of 180 degree phase-shifting regions for the alternating PSM, each group of 180 degree phase-shifting regions having a common size that is a different size than any other group. The size can refer to a width, a length, a width/length combination, or an area. In one embodiment, altering a transmission and a phase in the 2D simulation includes substantially matching a Fourier spectrum for the 3D simulation with a Fourier spectrum for the 2D simulation.

[0014] A method of designing a lithographic mask using this library is also provided. The method includes placing 0 degree phase-shifting regions and 180 degree phase-shifting regions on the lithographic mask. At this point, the library of pre-corrected shifters and matching simulation information can be accessed. Any 180 degree phase-shifting region having a size referenced in the library can be replaced with a corresponding pre-corrected shifter. The method can further include performing optical proximity correction (OPC) on the 0 degree phase-shifting regions and any pre-corrected shifters on the lithographic mask. In one embodiment, OPC can be performed using the matching

simulation information, thereby ensuring that the 3D compensation provided by the pre-corrected shifters is retained.

[0015] Thus, an alternating phase-shifting lithographic mask that compensates for 3D effects can include a plurality of 0 degree phase-shifting regions and a plurality of corresponding 180 degree phase-shifting regions, wherein each 180 degree phase-shifting region has a size based on its corresponding 0 degree phase-shifting region. Therefore, a first set of the 180 degree phase-shifting regions includes a first bias and a second set of the 180 degree phase-shifting regions includes a second bias, thereby selectively compensating for 3D effects caused by the 180 degree phase-shifting regions. Note that any reference to 0 and 180 degree phase-shifting regions is relative, not absolute. In other words, the difference in phase between the two phase-shifting regions is approximately 180 degrees. Thus, 3 degree phase-shifting regions and 182 degree phase-shifting regions could also be used in the methods herein described.

[0016] A system that compensates for 3D effects on an alternating PSM is provided. The system can include an input interface for receiving a layout of the alternating phase-shifting mask and an output interface for providing a modified layout that compensates for the three dimensional effects. A memory in the system can also include a plurality of original sizes for 180 degree phase-shifting regions on the mask, a plurality of pre-corrected sizes, a plurality of transmission values, and a plurality of phase values. Each original size has a corresponding pre-corrected size, transmission value, and phase value. The corresponding transmission value and phase value allow a 2D simulation for the corresponding pre-corrected size to substantially match a three dimensional simulation for the original size. The system can further include a plurality of computer-implemented programs for generating the corresponding

pre-corrected size, transmission value, and phase value. Finally, the system can include a processor for executing the plurality of computer-implemented programs.

BRIEF DESCRIPTION OF THE DRAWINGS

[0017] Figure 1A illustrates a top view of an alternating PSM including closely spaced opaque features formed on a transparent substrate.

[0018] Figure 1B illustrates a cross sectional view of the alternating PSM of Figure 1A.

[0019] Figure 1C illustrates a graph that plots intensity (0 to 1.0) versus position on the alternating PSM of Figures 1A and 1B.

[0020] Figure 1D illustrates a feature having a corresponding 0 degree phase-shifting region placed relative to one side of the feature and a corresponding 180 degree phase-shifting region placed relative to the other side of the feature.

[0021] Figure 1E illustrates a cross sectional view of an alternating PSM in which an additional etching step under-cuts certain features.

[0022] Figure 2 illustrates an exemplary layout that can compensate for 3D effects on an alternating PSM.

[0023] Figure 3 illustrates a flow chart of a process for building an equivalency library.

[0024] Figure 4A illustrates a flowchart of an alternating PSM design process.

[0025] Figure 4B illustrates an exemplary 180 degree phase shifting region including a first portion having a first transmission as well as a second portion having a second transmission.

[0026] Figure 5 illustrates a system that can compensate for 3D effects on an alternating PSM.

DETAILED DESCRIPTION OF THE DRAWINGS

[0027] To correct 3D effects while ensuring mechanical stability, a 180 degree phase-shifting region of an alternating PSM can be biased a predetermined amount larger than its corresponding 0 degree phase-shifting region. For example, Figure 2 illustrates an exemplary layout 200. Layout 200 could be in, for example, a GDS-II format or any other format providing feature information regarding one or more layers of an integrated circuit. In this simplified layout, a feature 201, e.g. a transistor gate, has an associated 0 degree phase-shifting region 203 and an associated 180 degree phase-shifting region 204. To ensure that feature 201 prints on a wafer consistent with centerline 202, the width (i.e. the dimension perpendicular of center line 202) of 180 degree phase-shifting region 204 can be increased by a bias 206. In one embodiment, the length (i.e. the dimension parallel to center line 202) of 180 degree phase-shifting region 204 can also be increased by a bias 207, wherein bias 206 could be equal to or unequal to bias 207. Therefore, an alternating PSM used for printing feature 201 could include 0 degree phase-shifting region 203 and a revised 180 degree phase-shifting region 204, i.e. 180 degree phase-shifting region 205.

[0028] Note that providing a general bias, i.e. an identical bias to all 180 degree phase-shifting regions on the mask, can increase the intensity of some 180 degree phase-shifting regions. However, as determined by Numerical Technologies, Inc., different sized phase-shifting regions and/or phase-shifting regions in specific orientations may require different biases to optimize intensity compensation. Therefore, in accordance with one feature of the invention, the bias can be selectively provided for each 180 degree phase-shifting region based on a simulation process described in reference to Figure 3. Selectively

providing a custom bias to each 180 degree phase-shifting region can dramatically improve the ability to match the intensity of that 180 degree phase-shifting region to its associated 0 degree phase-shifting region. Note, however, that the approach could be applied to all phase-shifting regions as appropriate (e.g. if 60 degree and 240 degree phase-shifting regions were being used, then both might be compensated to have equal intensity). For simplicity of discussion, shifters of phase 0 and 180 will be considered as they are most commonly used. However, the methods described herein can be used with shifters having other phase values.

[0029] The calculation of an appropriate bias can be performed using 3D simulation. However, determining the propagation of an electromagnetic field in a mask involves rigorous calculations. Specifically, these calculations solve Maxwell equations in three dimensions and then provide the calculated wave field to image formation software. Unfortunately, an accurate 3D simulation used repeatedly in any process would be extremely resource intensive, e.g. requiring significant CPU and memory resources, and time consuming, thereby rendering the process commercially unviable.

[0030] Therefore, in accordance with one feature of the invention, the use of 3D simulation is limited to obtaining accurate information regarding a 180 degree phase-shifting area on a one time basis. Thereafter, information derived from this 3D simulation can be used in a 2D simulation to closely approximate 3D accuracy. In one embodiment, to provide a commercially viable process, an equivalency library can be built that includes an original size, e.g. width and/or length, of a 180 degree phase-shifting region as generated by PSM tools and a corresponding shifter size to actually achieve the desired

printed image. (Note that a phase-shifting region is also referenced herein as a "shifter".)

[0031] Figure 3 illustrates a flow chart of a process 300 for building an equivalency library. Initially, a 3D simulation can be generated for an original width and length of a shifter, i.e. w_0 and l_0, in step 301. In a preferred embodiment, the electromagnetic field calculations of this 3D simulation are performed at a cut-line on the mask that is located just below the shallow trench that forms the 180 degree phase-shifting region, e.g. approximately 50nm, below the absorbing layer. Figure 1B illustrates a cut-line 109 located just below the trench forming the 180 degree phase-shifting region, i.e. aperture 107. Note that calculations performed at cut-lines below this level can break down due to cross-talk between adjacent regions. Therefore, in one embodiment, a Fourier spectrum can be generated for the 3D simulated shifter at this cut-line.

[0032] Note that in this 3D simulation a transmission T_0 of 1 and a phase Φ_0 of 180 degrees can be assumed. Performing 2D simulation on the same width/length shifter using transmission T_0 and phase Φ_0 typically yields a slightly different Fourier spectrum. An elegant method to compensate for this variation from the 3D simulation is to alter the transmission and phase. Specifically, in step 302, 2D simulation can be performed while altering the transmission and phase until the 2D simulation substantially matches the 3D simulation. In one embodiment, to determine a match of the Fourier spectrums for the 3D and 2D simulations, either linear correlation or linear regression can be performed, both of which are well known in the art. The shape dependent transmission T_F and phase Φ_F provide the necessary correction such that a 2D simulation can be performed with the same accuracy as a 3D simulation.

[0033] Specifically, using shape dependent transmission T_F and phase Φ_F in step 303, a shape dependent shifter width and length, i.e. w_F and l_F, can be chosen such that the Fourier spectrum from this shifter using 2D simulation matches the Fourier spectrum from the original shifter, i.e. having w_0 and l_0, using 3D simulation. The shape dependent shifter width w_F subtracted from the original shifter width w_0 is called the width bias, whereas the shape dependent shifter length l_F subtracted from the original shifter length l_0 is called the length bias. In step 304, these biases and the shape dependent transmission T_F and phase Φ_F can be associated with the original shifter width w_0 and length l_0 in the equivalency library. In one embodiment, the shape dependent width w_F and length l_F can used instead of the biases or in addition to the biases.

[0034] In one embodiment for building the equivalency library, the 180 degree phase-shifting regions having the same width/length can be identified on the alternating PSM. Then, the above-described process 300 can be repeated for each width/length combination, which could number in the hundreds or even thousands. In one embodiment, the shifter widths/lengths can be replaced with shifter areas (i.e. not including specific widths and lengths, but instead the total areas associated with the shifters), thereby potentially reducing the number of simulations to be performed. Note that using shifter areas instead of shifter widths/lengths can address the issue of irregular-shaped shifters, i.e. those shifters having other than four edges.

[0035] Of importance, the most resource intensive (and thus expensive) as well as time-consuming step, i.e. step 301 of generating the 3D simulation, is only done once for each width/length shifter. The subsequent steps 302 and 303, which are performed using 2D simulation, can be performed inexpensively and quickly. Additionally, once steps 301-304 in process 300 are

performed, the stored information in the equivalency library can be used for any alternating PSM mask generated using similar processes. Thus, as described in further detail below, the invention also advantageously provides a layout-independent process that can accurately compensate for 3D effects during alternating PSM design.

[0036] Figure 4A illustrates a flowchart of a PSM design process 400 in accordance with one embodiment. In step 401, the equivalency library can be built using process 300 (Figure 3). In step 402, a standard PSM process can be used to place pairs of phase-shifting regions, wherein each pair includes a 0 degree phase-shifting region and a 180 degree phase-shifting region, in operative relation to corresponding critical features (see Figure 2). In one embodiment, a software tool, such as the iN-Phase™ tool licensed by the assignee of the invention, can be used to identify the critical features in a GDS-II file, generate a binary mask layout including a set of these critical features, and generate a PSM layout that places non-conflicting 0 degree phase-shifting regions and 180 degree phase-shifting regions in operative relation to the set of critical features. Note that the equivalency library is equally applicable to any process and/or software than can identify the (180 degree) phase-shifting regions on a mask.

[0037] Any one of multiple methods can be used to correct 3D effects, as indicated by step 403. Using one method, in step 404, the currently placed 180 degree phase-shifting regions can be replaced with the pre-corrected 180 degree phase-shifting regions stored in the equivalency library. Thus, for example, all 180 degree phase-shifting regions of width w_0 and length l_0 can be replaced with 180 degree phase-shifting regions of width w_F and length l_F. In one embodiment, a pre-corrected shifter is chosen and all currently placed 180 degree phase-shifting regions

on the mask are examined to determine if one or more of these currently placed shifters should be replaced. If replacement occurs, then these shifters need not be examined when the next pre-corrected shifter is chosen. In another embodiment, each currently placed 180 degree phase-shifting region is chosen and the library is queried whether a pre-corrected shifter exists for that width/length phase-shifting region.

[0038] Once replacement is complete, if desired, standard OPC, e.g. either rule- or model-based, can be performed in step 405 using the pre-corrected (i.e. modified) shifters as the reference layout. Note that standard OPC using 2D simulations to make the corrections can now be used.

[0039] In another method, as indicated in step 406, the shape dependent transmission T_F and phase Φ_F can be used to perform the OPC on the phase mask while initially retaining the shifters placed in step 402. Specifically, instead of pre-biasing the 180 degree phase-shifting regions on the phase-shifting mask and performing standard OPC, OPC can be performed while using the appropriate shape dependent transmissions T_F and phases Φ_F. For example, referring to Figure 4B, a feature 421, e.g. a transistor gate, has an associated 0 degree phase-shifting region 423 and an associated 180 degree phase-shifting region 424. To ensure that feature 421 prints on a wafer with the appropriate CD control and positioning relative to the rest of the layout, e.g. including the feature 425, OPC can be performed on the phase-shifting regions 423 and 424. As shown in Figure 4B, this approach can even work when the shifter is not a rectangle.

[0040] In accordance with one feature of the invention, multiple phases and transmissions can be associated with any shifter. Thus, for example in Figure 4B, 180 degree phase shifting region 424 can include a first portion 424(1) having a

first transmission as well as a second portion 424(2) having a second transmission.

[0041] Model-based OPC of phase shifting region 424 along the edge that abuts feature 421 will now be considered. For illustrative purposes, dissection points (indicated by a thick dashes) and evaluation points (indicated by thick plus signs) that will be used during the OPC process are shown along the edge. Separate phase and transmission information for the phase shifting regions 424(1) and 424(2) can be provided in the equivalency library. Note that such a library can be built using steps 301-304 (Figure 3) for each portion associated with a 180 degree phase shifting region. In one embodiment, the library is constructed in part concurrently with the OPC process of step 406. Thus, as dissection points are placed along shifters, the shifter shapes, e.g. phase shifting regions 424(1) and 424(2), are run through the process of Figure 3. This may be useful because a single phase shifting region, e.g. the phase shifting region 424, could be divided into any number of different shaped rectangles.

[0042] Continuing the example, as model based OPC is performed on the phase shifting region 424(1), the shape dependent transmission and phase T_F and Φ_F, respectively, can be used in the 2D simulation to compute optical effects and adjust the shape of the phase shifting region 424(1).

[0043] Note that any 2D simulation performed after step 302 can advantageously use the shape dependent transmission T_F and phase Φ_F to provide more accurate results. Thus, by using process 300, tools that perform 2D simulation can be appropriately modified to provide 3D accuracy.

[0044] Figure 5 illustrates a system 500 that can compensate for 3D effects on an alternating PSM. In one embodiment, system 500 can include an input interface 501 for receiving a layout of

the alternating PSM and an output interface 505 for providing a modified layout that compensates for the three dimensional effects. System 500 can also include a memory 506 that stores an equivalency library 502 as well as a plurality of computer-implemented programs 503(1)-503(N) for implementing the steps described in Figures 3 and 4. In a typical embodiment, system 500 can further include a processor 504 for executing computer-implemented programs 503 and accessing library 502 as appropriate. Note that computer-implemented programs 503 can be run on any number of computer platforms including: a PC using the Windows 95™ or NT™ 4.0 operating system with 128 MB of RAM and a 200 MHz Pentium Pro™ microprocessor, either stand alone or connected to a network, and a SUN™ workstation computer among others.

[0045] Although illustrative embodiments of the invention have been described in detail herein with reference to the accompanying figures, it is to be understood that the invention is not limited to those precise embodiments. They are not intended to be exhaustive or to limit the invention to the precise forms disclosed. As such, many modifications and variations will be apparent. For example, in one embodiment, rather than using a 3D simulation as part of process 300 (Figure 3), measurements from a test exposure can be used to develop the appropriate shifters. In this embodiment, the actual test exposure measurements for a given test pattern can be compared with the 2D simulation values. Adjustments can be made to the shifter until the 2D simulation values match the test exposure. Note that the methods described herein can be applied to a variety of lithographic process technologies, including ultraviolet, deep ultraviolet (DUV), extreme ultraviolet (EUV), x-ray, and ebeam. Accordingly, it is intended that the scope of

the invention be defined by the following Claims and their equivalents.